Chapter 10

The Use of Computed Tomography to Explore the Microstructure of Materials in Civil Engineering: From Rocks to Concrete

Miguel A. Vicente, Jesús Mínguez and
Dorys C. González

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.69245

Abstract

Computed tomography (CT) is a nondestructive technique, based on absorbing X-rays, that permits the visualisation of the internal microstructure of material. The field of application is very wide. This is a well-known technology in medicine, because of its enormous advantages, but it is also very useful in other fields. Computed tomography is used in palaeontology to study the internal structure of the bones from ancient hominids. In addition, this technology is being used by engineers to analyse the microstructure of materials. Materials engineers use this technology to analyse or develop new materials. Mechanical engineers use CT scans to study the internal defects of materials. Geotechnical engineers use CT scans to study several aspects of the rocks and minerals (cracks, voids, etc). This technology is also very useful to study de microstructure of concrete, especially in case of the new concretes (ultra-high performance concrete, fiber reinforced concrete, etc). In this chapter, an extended state-of-the-art of the most relevant research, related to the use of computed tomography to explore the microstructure of materials in civil and mechanical engineering, is exposed. The main objective of this chapter is that the reader can discover new applications of the computed tomography, different from conventional ones.

Keywords: CT scan, rocks, high performance concrete, fiber-reinforced high performance concrete

1. Introduction to computed tomography (CT) scan technology

Ever since Wilhelm Röntgen discovered X-rays in 1895, these rays have been used in many scientific fields. One property of this type of radiation is that it can travel through matter, losing energy on the way, in accordance with the law of Beer that equates intensity I with a monochromatic X-ray travelling through an object in terms of the following expression (Eq. (1)).

$$I = I_0 \cdot exp\{-\int \mu(s)ds\} \tag{1}$$

where I_0 is the initial intensity of the ray and $\mu(s)$ the linear attenuation coefficient along its trajectory.

The aforementioned linear attenuation coefficient, μ, fundamentally depends on the density, ρ, of the material at each point through which the ray travels. The quotient μ/ρ is approximately proportional to Z^3 in the standard range used in the computed tomography (CT) scans, where Z is the atomic number of the element.

CT is a nondestructive technique used to analyze the internal microstructure of materials based on the above-mentioned property of X-rays. The tomography equipment is composed of an emitter, which emits a ray at a given intensity, and a detector, which registers the reception intensity of the ray. In the analysis, the object revolves in front of the apparatus, consisting of the emitter, emitting rays in all directions on the plane, and the detector. Postprocessing of the signal to produce attenuation-corrected images, which coincide with the measurement of attenuation, means that the density of each point of the specimen under study may be determined. This process is repeated for different sections of the specimen, thereby obtaining tri-dimensional (tomographic) information. Alternatively, a conic beam of X-rays can be emitted that are collected on a flat detector. In this case, only the specimen has to revolve, and relative displacement between the emitter-detector apparatus and the specimen is unnecessary (**Figure 1**):

In all cases, the practical result is a tri-dimensional image, in grey scale, in which each grey area corresponds to a particular density value. Clearer tones represent higher densities, and darker tones represent lower densities.

The use of this technique commenced in medicine, during the last century, around the 1970s, as a non-invasive technique to explore the internal parts of patients, to display the inside of the body (organs, tissue, bones, etc.) and to detect abnormal structures that can indicate some pathology.

Over recent years, the technique has been discarded in medicine; however, it has been used in a more intense way in other scientific fields, especially science and engineering, where all variants of computerized tomography are increasingly employed.

In the 1980s, high-resolution tomographic equipment emerged commonly called micro CT scan. This new equipment used new sources of emissions, in the form of gamma rays and synchrotron radiation. At present, synchrotron radiation is the most widely used in modern equipment because of its high resolution and sharpness.

There are substantial differences between a CT scan for medical purposes and a CT scan in research and in the industrial sector. In the former case concerning medical equipment, the specimen or patient remains immobile, and it is the emitter-receptor apparatus that moves and revolves. However, it is the specimen that is moved and turned in an industrial or research CT scan.

Moreover, the equipment used in medicine presents very low intensity values because of the effects of high radiation on human health. These levels of radiation result in lower resolution and sharpness (**Figures 2** and **3**):

http://dx.doi.org/10.5772/intechopen.69245

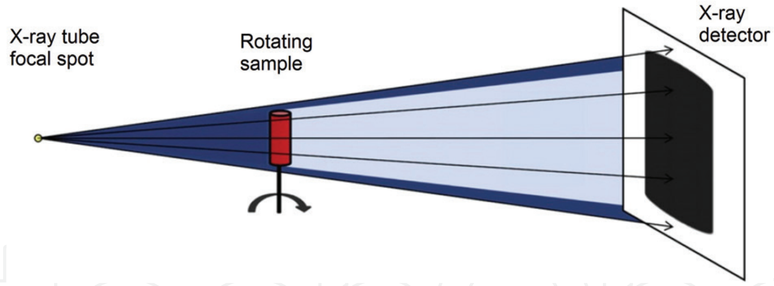

Figure 1. The principle of the working of a CT scan [1].

Figure 2. An example of medical CT scan. Courtesy of Siemens.

Figure 3. An example of medical CT scan. Courtesy of YXLON.

2. Use of CT scan technology in paleontology

Paleontology is one of the first scientific fields in which the use of computerized tomography started outside of medicine. Obviously, the technique of analyzing the bones of hominids and dinosaurs hardly differs from the technique used with humans and animals that are alive.

Numerous research papers have published studies in this field in which the CT scan is a very valuable instrument.

The fossilization process of an organism takes place over thousands of years, during which time loss and fragmentation of bones and other hard parts of the skeleton, decomposition, and so on occur. In addition, breakage occurs during their manipulation and study, which can imply an enormous loss. The primary objective of paleontological investigation is the reconstruction of skeletons and, from that point, to interpret many other biological and environmental characteristics, and so on.

The CT scan is a very useful tool here because it permits exact tridimensional images and, by means of software for the post-processing of images, can reconstruct skeletons without any need to manipulate the pieces. In addition, the information collected by the CT scan can serve as the basis for the regeneration of exact replicas using 3D printers [2–6].

In other cases, it may be physically impossible to remove the rocky sediment that hardens around the fossil. In that case, the CT scan can virtually eliminate it, revealing the "clean" piece [7] (**Figure 4**):

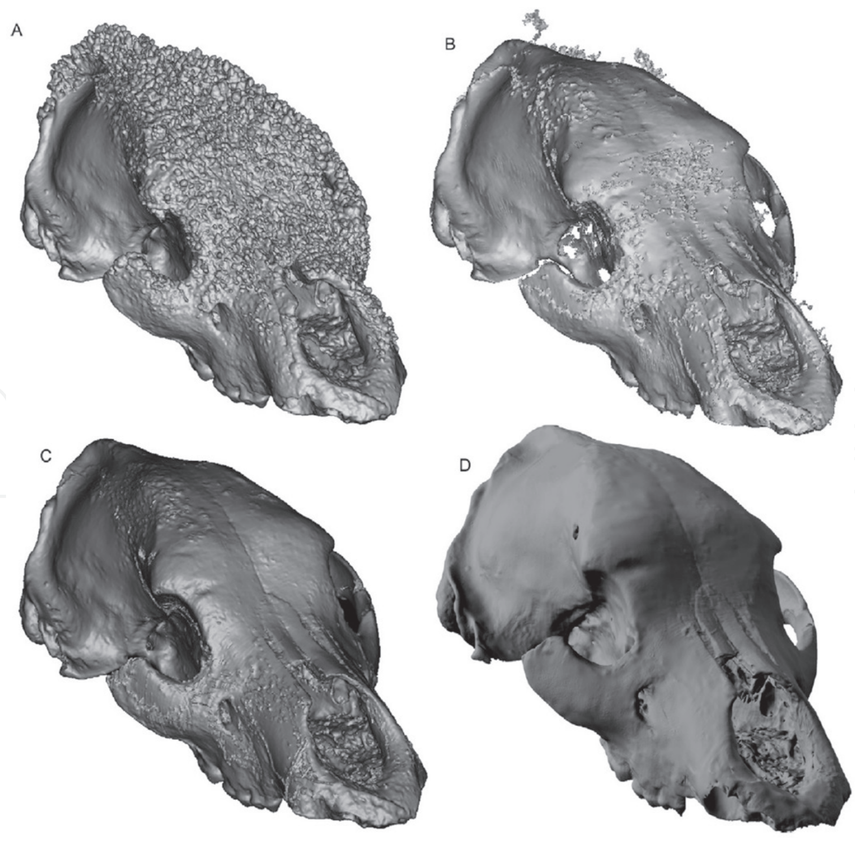

Figure 4. Virtual reconstruction and cleaning [7].

http://dx.doi.org/10.5772/intechopen.69245

In other cases, the CT scan can determine the biomechanical parameters of the fossils [8] and detect disease and pathologies [9].

Recently, some research works have been published, in which possible alterations to the sample, due to the radiation emitted by the CT-Scan in the course of dating studies, are analyzed [10, 11].

3. Use of CT scan technology in heritage and ancient relics

Relics and ancient artifacts, to some extent, share the characteristics of fossils, explained in the earlier section. In the first place, these objects are of singular value, so they have to be handled with great care. In many cases, they are pieces that have remained buried for thousands of years and may be covered by layers of rocky sediment that is strongly attached, the mechanical removal of which implies a serious problem for the piece.

In these cases, the use of CT scan technology is of enormous interest. In the first place, the archaeological piece may be separated from the surrounding sediment as a virtual replica. In this way, the piece may be examined with the naked eye and studied without damaging it. Moreover, on the basis of the information obtained by the CT scan, exact replicas of the piece may be produced, using 3D printers. This option allows researchers to manipulate the replicas and to study them without the dangers, and the limitations involved in handling the original piece. It is also of interest for museums, as they can exhibit the replicas, for keeping the original piece safe in storage [12–16]. (**Figure 5**).

In other cases, the pieces are extremely delicate, such as paintings [17] and mummies [18]. In both cases, an analysis by means of CT scan technology preserves the integrity of the piece.

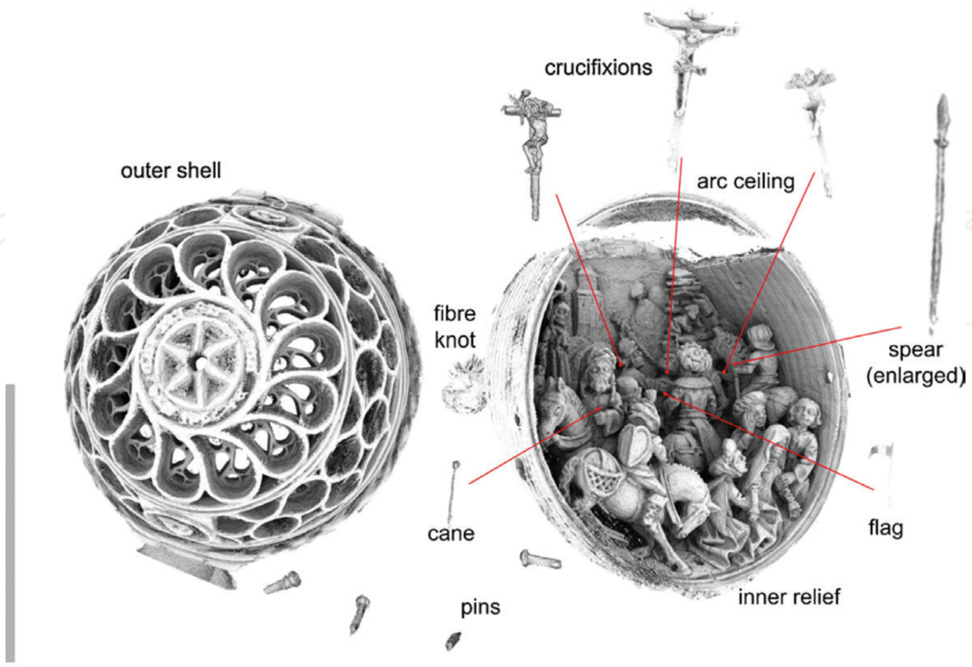

Figure 5. An example of rendering a prayer nut [12].

4. Use of CT scan technology in asphalt mixtures

Asphalt mixtures are widely used in the construction of road pavements and airports, because of the advantages that they contribute, among which are high strength, easy manufacturing and maintenance, low noise emission, and so on.

From the structural point of view, asphalt mixtures are heterogeneous materials, composed of aggregates, asphalt, and porous networks. Their mechanical properties show high levels of dispersion, given that those properties depend on many factors, such as the form and the distribution of the aggregate, the asphalt content, the pore content, pore distribution, and so on.

Comparative numeric models, as close as possible to the real specimens, need to be developed, in order to understand the behavior of the asphalt mixtures better. In this sense, the CT scan is of great assistance, as it generates the exact geometry of the internal structure of the asphaltic mixture and subsequently a finite elements model (FEM) with which the real capacity may be estimated against certain external actions. Comparing the numerical results with the tests carried out on the real specimen, it is possible to advance in the calibration of these models that predict the behavior of the material to improve its properties [19–23] (**Figure 6**).

In the case of special asphalts, it may be of great interest to know the exact distribution of certain compounds, with a view to understand their effectiveness. This situation applies to both additives for pavement restoration [24] and fiber-reinforced asphalts [24]. In many cases, with the assistance of the CT scan, correlations are sought between the mechanical behavior of the asphalt mix and its internal microstructure [25–28].

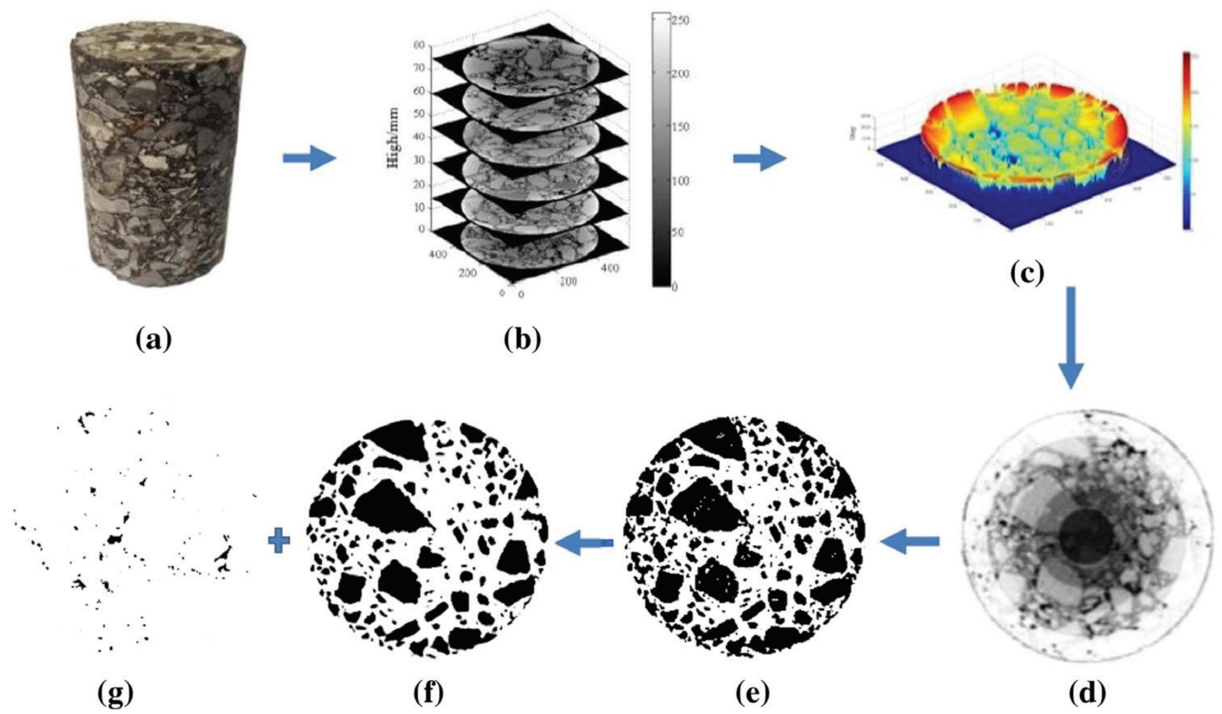

Figure 6. Extraction of the area of interest using CT scan technology [19].

http://dx.doi.org/10.5772/intechopen.69245

5. Use of CT scan technology in rock mineralogy

Since the 1980s, research has taken place in which CT scan technology has been applied to the analysis of the internal microstructures of rocks.

Rocks are heterogeneous materials containing pores and fissures and consisting of various materials, with different mechanical properties and of varying density. On many occasions, the structural behavior of a rock is strongly conditioned by its microstructure, especially in reference to pores and fissures.

Rock, as a structural material, is present in a range of civil engineering works, among which tunnels and dams are prominent. In tunnels, the mechanical characteristics of the rocks, their porosity, and their degree of internal fracturing strongly condition their stability, their convergence, and so on.

Something similar occurs in the case of dams, especially arch dams. These structural elements are cemented to rock faces, and their structural safety is strongly dependent on the mechanical behavior of the rocks. The existence of failure planes or excessive internal fissuring might mean that the dam is not stable against the loads that it transfers, or it is not sufficiently watertight to ensure the retention of the water in the reservoir.

The foundations of large bridges, generally very deep foundations constructed with piles, usually reach down to the bedrock. Once again, the geological and mechanical characteristics of the rock clearly determine the structural safety of the bridge.

The possibilities offered by CT scanning in the field of geo-mineralogy are enormous [1, 29–31]. In all of these cases, CT scan technology has been successfully used to understand the microstructure of the bedrock and its behavior in reaction to certain physical and mechanical processes (**Figure 7**).

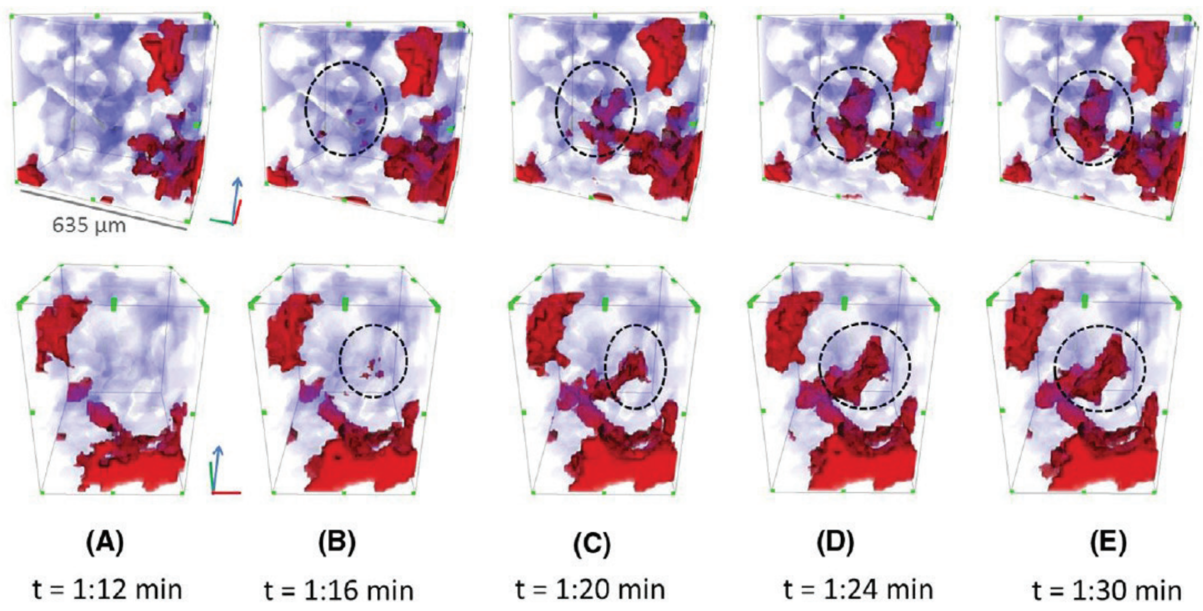

Figure 7. Example of the possibilities of CT scan technology in rocks [29]. This time, the sequence shows a pore filling event.

Porosity, linked to water absorption capacity, is a very important parameter in rocks, as demonstrated by the high number of scientific publications in this field. At present, the most relevant investigations are currently applying CT scan technology to evaluate porosity, regardless of whether it has structural consequences [32, 33]. Other investigative works have analyzed mechanical behavior and its connection with the mineralogical microstructure [34].

One of the variants of this theme is the study of petrous elements for their use in construction. A theme of great interest is the study of porosity in limestone used, for example, in façades and pedestrian pavements, as well as for the rehabilitation of historic buildings and as a masonry element. In all of these cases, determination of the porosity of limestone is essential when determining whether it is convenient for use in a particular climate. In the case of environments subjected to freezing-thawing cycles, a high porosity substantially reduces the working life of the limestone.

On this point, it is worth highlighting the studies developed by Dewanckele et al. [35] and Boone et al. [36], in which the behavior of porous limestone was analyzed against erosive processes and water absorption. To do so, CT scanning was used to analyze how the internal structure of the limestone evolves due to the aforementioned processes (**Figure 8**).

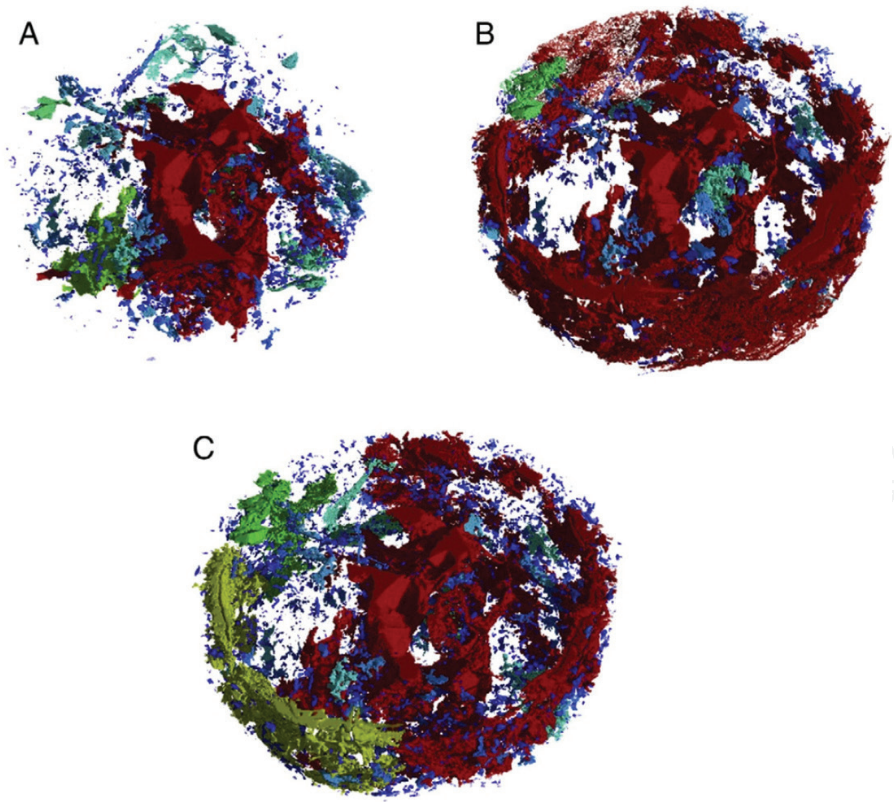

Figure 8. The example of rendering volumes of the changing pores in limestone [35]. The pores are color coded from red (large) to blue (small). Drawing A belongs to unweathered state, drawing B belongs to 6 days of weathering process, and drawing C belongs to 21 days of weathering process.

6. Use of CT scan technology in metals

Metals are widely used materials in the industrial sector. At present, innumerable types of simple metals and alloys are used, each one of them with specific properties, useful for the function that they have to perform: very light or carrying heavy loads, electrical conductivity or otherwise, high and low thermal transmissivity, tenacity and fracture strength, abrasion resistance, hardness, mechanical capacity, corrosion resistance, and so on.

Metals are used in all fields of industrial engineering, without exception. Metal manufacturing processes are very varied, ranging from smelting and casting to more modern systems of stamping and injection. In general, the metals used in different fields present optimal properties for the function they will serve, with the optimal design of parts in terms of material consumption.

The use of CT scan technology is quite widespread in the industrial sector, especially in those sectors that develop elements of high added value (aeronautical, aerospatial, automotive sectors, etc). One very common line of investigation, in which CT scan technology plays a relevant role, is the study of defects produced during the manufacturing process, with a view to their improvement [37–40]. In some cases, comparisons have been established between the microstructure of the material and its mechanical behavior [41–44]. In these cases, the information obtained by means of CT scanning is used for the generation of the tridimensional FEM models for the numerical simulation of the expected results and their subsequent comparison with the values measured in the tests. Here, the advantage of CT scanning is that it permits the construction of exact numerical models, which not only includes the different phases that constitute the piece but also the pores, defects, fissures, and so on in their exact position (**Figure 9**).

Within this line of investigation, it is worth highlighting welded joints and their analysis [45]. Welding is the most extensive process, whenever possible, for joining together two metallic parts. The way in which the welding is done is fundamental to the final quality of the joint.

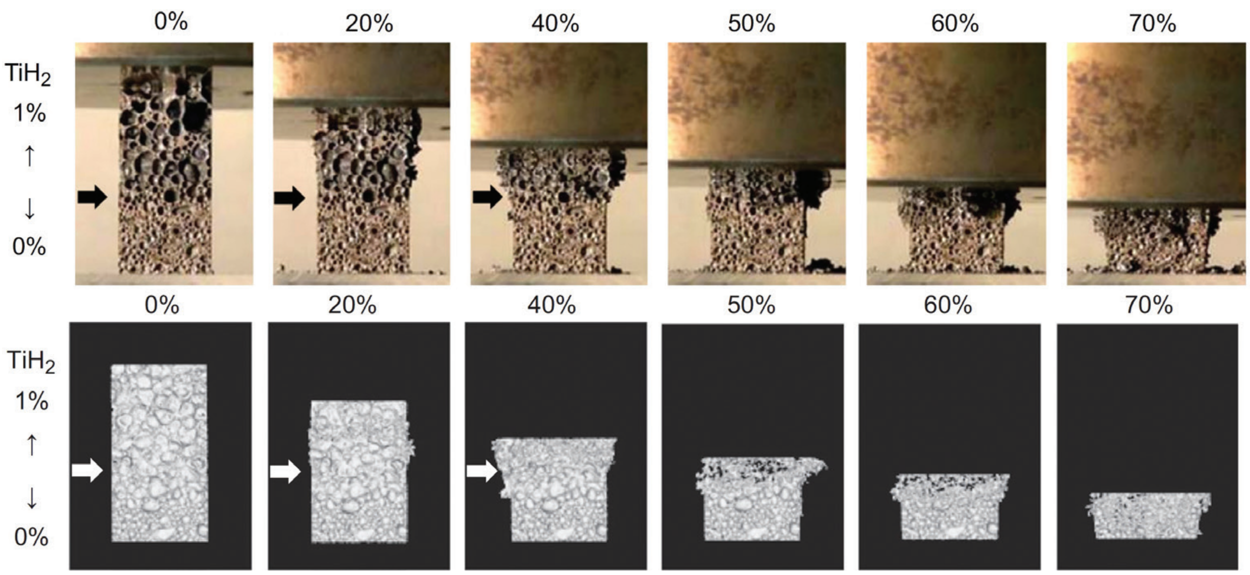

Figure 9. The example of an analysis of mechanical behavior of metal under compression and CT scan analysis [44]. (a) Sequential deformation recorded with a video camera and (b) sequential deformation “recorded” with a CT scan.

In this sense, as in the earlier case, the defects produced in the weld can be evaluated during welding with CT scan technology helping to improve the process.

One particular case of metals, used from a structural point of view, is composite metals, generally composed of a bland or foamy metallic matrix to which fibers or particles are usually added to improve their rigidity and strength [46]. In these cases, the microstructure of the composite material may be analyzed with CT scan technology, evaluating the distribution of the reinforcement, its orientation in the case of fibers, and so on.

7. Use of CT scan technology in composites

Composite materials are widely used in engineering. They are generally composed of a matrix and reinforcement that is generally of particles or fibers. The reinforcement has the role of modifying the natural properties of the matrix, with the objective of achieving a material of the desired characteristics.

In general, in a composite material, three phases may be distinguished: matrix, reinforcement, and pores or cracks.

The behavior of the composite materials strongly depends on the distribution and the orientation of the reinforcement (the latter solely in the case of fibers) as well as the location in the pores and cracks.

Of great interest in this field, CT scan technology permits the evaluation of the microstructure of the composite material [47–52]. In many cases, the combined use of CT scan and mechanical or thermal characterization tests of the composite material allows relations to be established between the microstructure and its macroscopic response [53–57] (**Figure 10**).

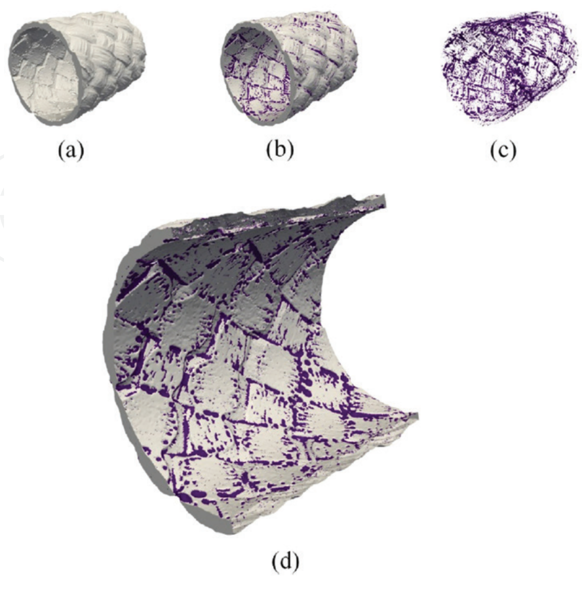

Figure 10. The example of analysis of the microstructure of a composite [47]. (a) 3D braid geometry, (b) 3D braid geometry with imperfections, (c) 3D distribution imperfections, and (d) detailed view.

http://dx.doi.org/10.5772/intechopen.69245

As commented in earlier sections, a CT scan is the basis for the generation of exact FEM models, from which numerical simulations of all kinds may be performed [58, 59].

8. Use of CT scan technology in concrete

Concrete is one of the most widely used materials in the construction of infrastructure and buildings. One of the reasons for its extensive use is the relatively low price of extracting petrous materials from the environment. Another reason is the possibility of molding its geometry as it is poured in the fresh (fluid) state. The composition of concrete is highly heterogeneous as its matrix is composed of different materials: cement, sand, and rough aggregate. The dosages of those elements are modified to obtain optimum mechanical capacities. Additionally, other types of materials are used to improve the performance of the concrete such as fibers and additives to modify the internal structure of the material.

Internally, what is generated is a matrix composed of aggregate fines and hydrated cement that cover the coarse aggregate (**Figure 11**).

It is noteworthy that there are a multitude of parameters with a role in the final characteristic. The dosages of the different components are based on experimentation due to the different typologies or aggregates, sand, and cement that are available on the market. As an example, if in one region, the rocky material in the surrounding environment is granite, the aggregate will be based on this material.

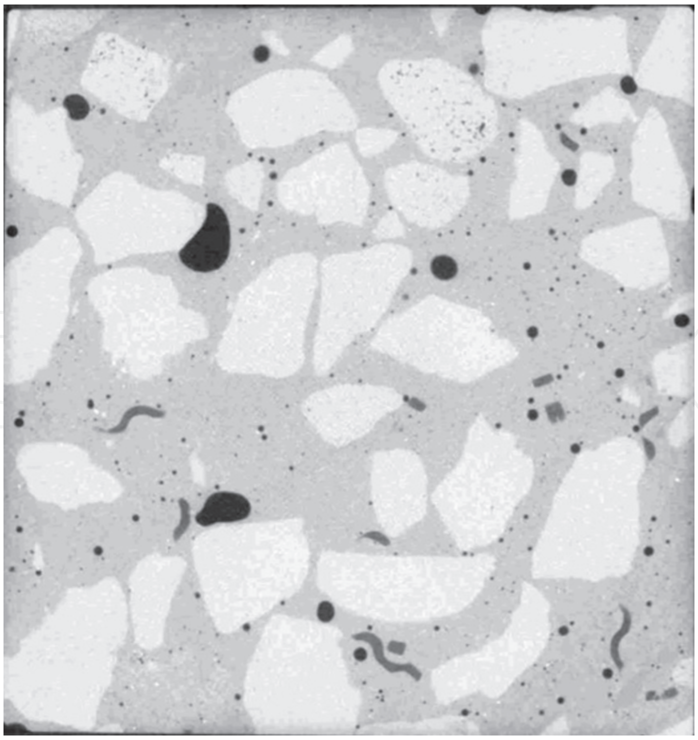

Figure 11. Polypropylene fiber-reinforced concrete specimen. Aggregates (in white), cement matrix (in soft grey), polypropylene fibers (in dark grey), and porous (in black) can be identified. Courtesy of the University of Burgos (Spain).

Moreover, concretes with additional qualities are under development in which fibers are added to their mixtures. There is at present a large quantity of fiber typologies in the market, so that at present, there is a broad process of investigation aimed at generating an optimal concrete in accordance with the desired performance.

Besides, public administrations are considering sustainability criteria that imply the development of research that aims to produce concrete that incorporates recycled materials, so as to reduce the carbon footprint and the environmental impact.

Therefore, in view of the above, it may be said that even though concrete is a priori a relatively rough and ready technology, constant development and improvements in performance, as well as new applications in construction elements are topics that are in the investigative projects of universities and research centers throughout the world.

New tools that provide the researcher with information to supplement the results of conventional tests have been incorporated to analyze concrete in this process of innovation for the determination of mechanical characteristics.

One of these tools that can be used to analyze the internal matrix of concretes and mortars is the computed tomography scan. The researcher is capable of analyzing unaltered samples of concrete in a non-destructive way, for example, in order to determine whether certain geometric patterns exist that can in turn classify the physical characteristics of the sample.

Next, some of the practical applications of computerized tomography to concretes are described.

8.1. Application to the analysis of the internal matrix

Among the applications of the CT scan technology for the analysis of a concrete matrix, there are some experimental studies focused on recycled concretes [60]. In these studies, concretes with equal percentages of 50% recycled aggregate (RCA) and 50% natural aggregates were analyzed. The objective of the use of tomography is to evaluate the interfaces between both types of concretes. In addition, the porosity of each type of matrix is analyzed (**Figure 12**).

The identification of pores provides information on these internal gaps that the matrix presents. This information may relate to the size of the pores and their distribution within the specimen. Information may also be extracted on the sphericity of the pores that is compared with a perfect sphere and finally, the spatial position of these pores within the matrix [61] (**Figure 13**).

The application of superabsorbent polymers (SAP) for the development of high performance concretes with the aim of reducing hydration-related problems of the cementitious matrix generates variations in the distribution of the pores within the concrete matrix and its porosity. These changes lead to modifications in the physical properties of the component [62].

Images of the spatial distribution of the pores may be obtained by means of computerized topography image analysis and the use of post-processing tools including volumes, numbers of pores, positions within the specimen, and sphericity indexes.

In this way, researchers can determine how the porosity map of the specimen is modified for different types of SAP additions (**Figure 14**).

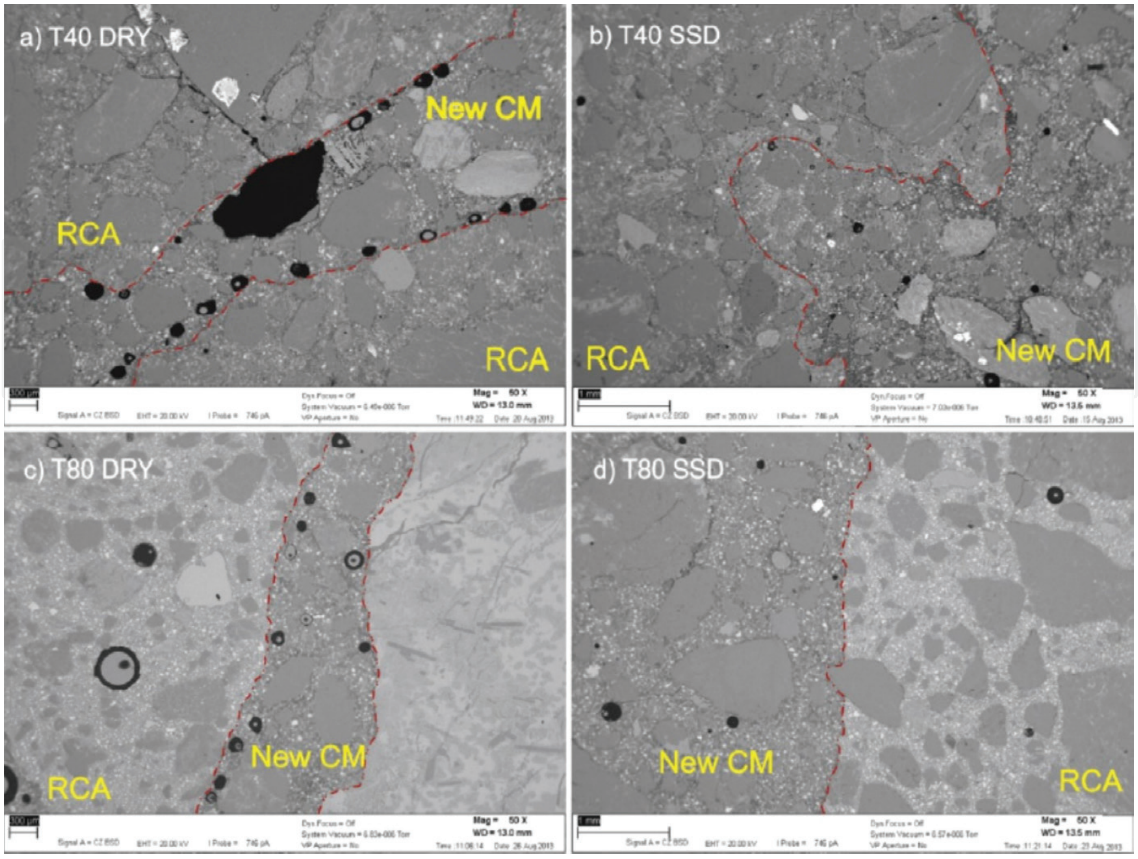

Figure 12. Interface paste-aggregate and porosity between matrices with recycled aggregates and natural aggregates [60].

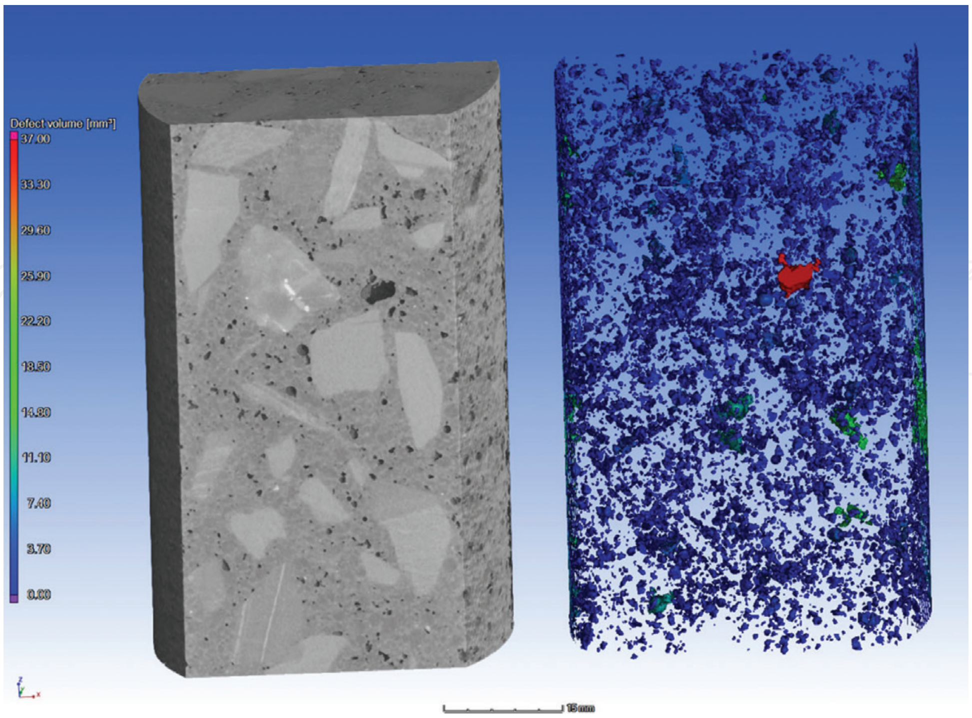

Figure 13. Identification and classification of pores in sizes [61].

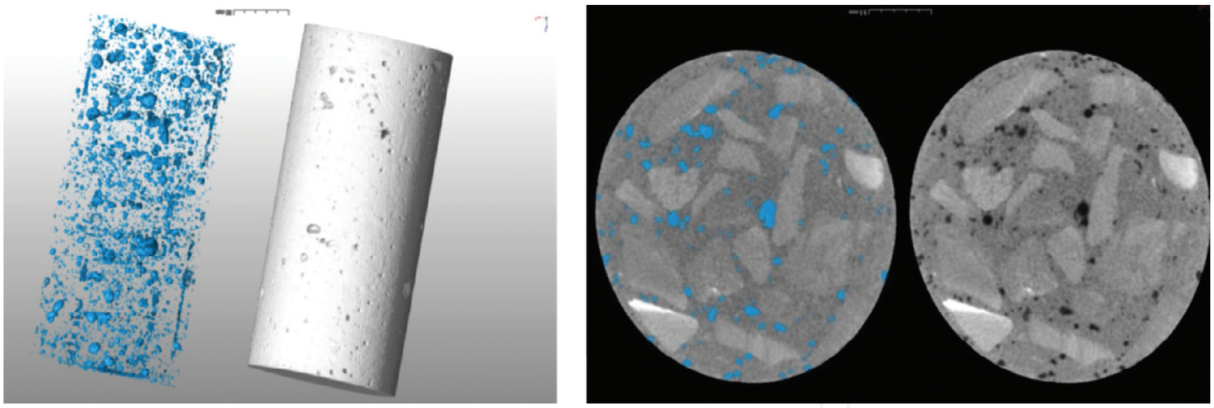

Figure 14. Identification of pores inside concrete matrix [62].

In addition to the pores, the distribution of polymeric components is established. In the following image, the way each of the components of the polymer is obtained following segmentation and their grouping is shown (**Figure 15**).

8.2. Applications to visualize fiber distribution

The addition of fibers improves the characteristics of concretes used in many different applications. The clearest and most widely used application is for the improvement of mechanical performance. The fibers withstand traction forces that the concrete is incapable of withstanding. As with all petrous materials, concrete presents a very good capacity to withstand compressive forces, while its resistance to traction stress is relatively low.

Hence, the need to add strengthening elements, in the form of fibers to resist traction forces, is necessary.

By way of an example, fibers are in a phase of expansion in their application to self-compacting concretes. The distribution and quantity of fibers represent a fundamental role in the final stress-resistant capacities of the concrete element [63].

Another factor that influences the mechanical capacities of fiber-reinforced concretes is fiber orientation within the matrix in relation to the traction planes of the component.

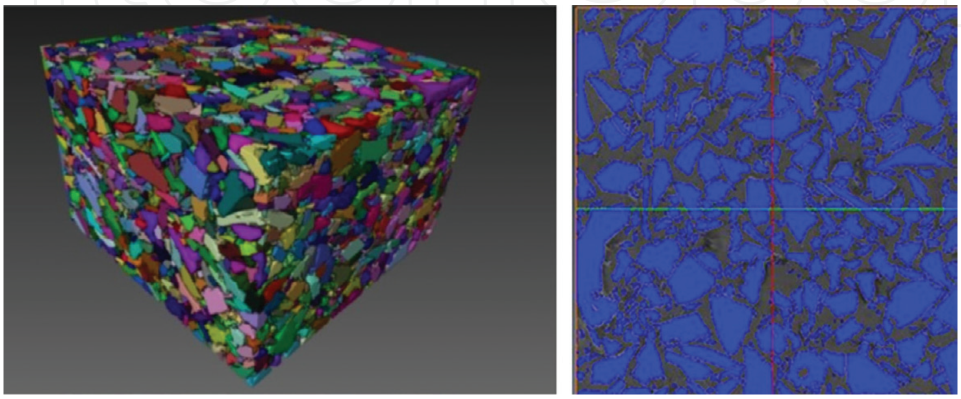

Figure 15. Segmentation and packing of the concrete matrix [61].

There are different segmentation techniques for the determination of fiber orientation [64, 65] (**Figure 16**). In all cases, they begin with a common process divided into different phases:

1. In the first phase, it is necessary to separate those materials that correspond to the concrete matrix by means of a grey-scale threshold.
2. In the second phase, the voxels that correspond to the same fiber have to be separated, in an attempt to separate those groups of fibers that may be in contact with other groups.
3. Once each fiber has been identified and separated, it is possible to obtain the orientation of each fiber and to identify its position in space.

Another application of computerized axial tomography consists of analyzing the way in which the fibers may be distinguished during the manufacturing process of pre-fabricated elements and how that affects the reinforcement bars in the element [66] (**Figures 17** and **18**).

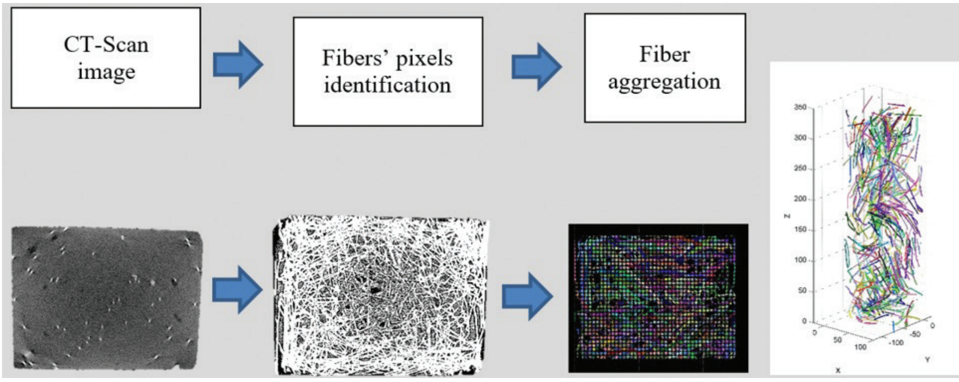

Figure 16. Procedure to identify fibers. The courtesy of the University of Burgos (Spain).

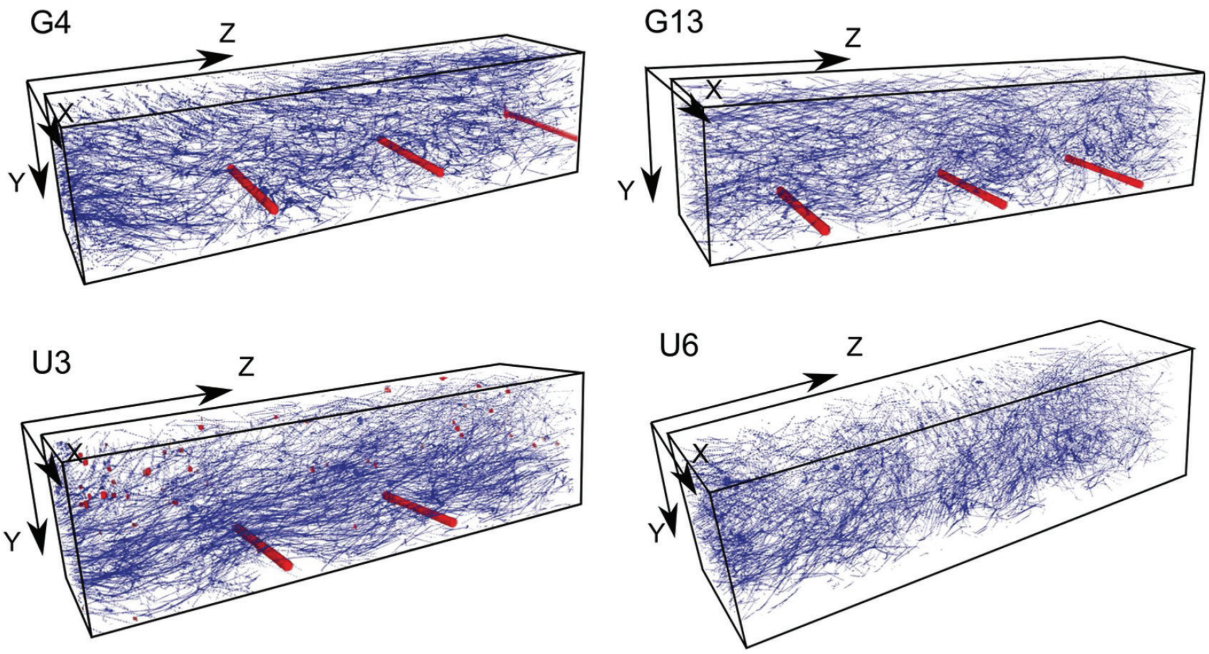

Figure 17. Fiber distribution around longitudinal rebars [66].

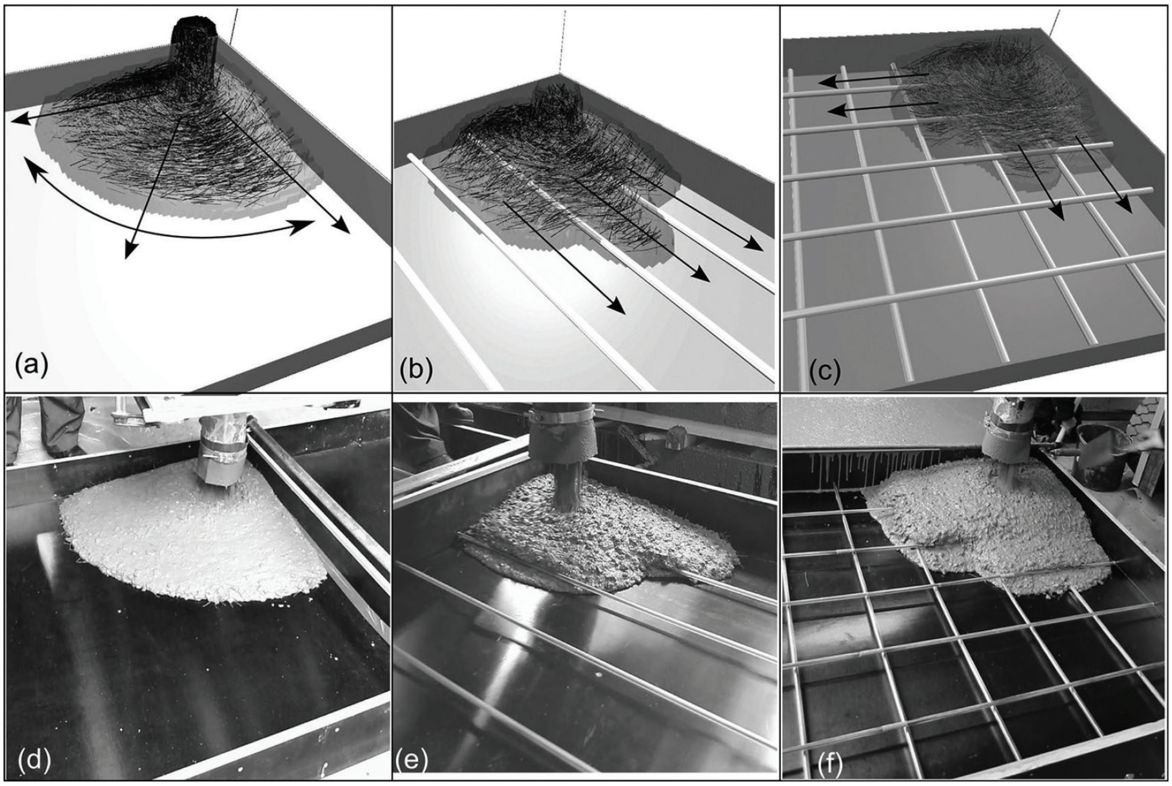

Figure 18. Schema of the fiber distribution and orientation during casting process [66].

8.3. Applications on internal analysis and cracking

The technology of the CT scan allows researchers to conduct analyses of concrete at a macro-level to identify the damage that may be generated in its matrix due to physical and chemical factors.

As described in the above sections, three-dimensional maps may be generated with this tool, which help the researcher to understand the internal mechanics of the concrete. There is at present no other real alternative that can reach the sub-millimetric level of detail of which tomography is capable.

In the case of the practical application carried out by Kim, Yun, and Park [67], CT scan technology was used to analyze samples of concrete and mortar at high temperatures. The objective was to determine how variations in temperature affected the behavior of the internal pores of the material until their collapse. In the following image, the fissures that developed when the concrete was subjected to 1000°C are shown (**Figures 19** and **20**):

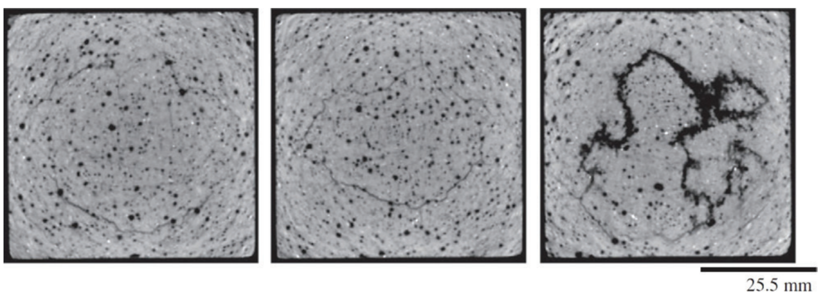

Figure 19. Fracture development at 1000°C [67].

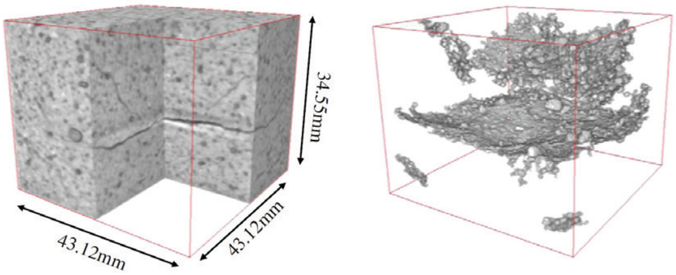

Figure 20. Imaging of fractures that developed at 1000°C [67].

It was determined that the appearance of fissuring began at a temperature of 600°C, and that this damage fundamentally began to occur in the zones close to the edges of the specimen, in the external zones, progressing as the temperature increased towards critical values until it reached a point of collapse.

Other studies related to fracture mechanics have analyzed how the fissuring of an element evolves when subjected to a flexural-traction test by using scanned images, in order to create a finite element model and a model of discrete damage adjusted to the physical interactions detected in the images [68] (**Figure 21**).

Finally, the following paragraphs describe research work that has been developed to determine the damage produced under cyclic loading in concrete specimens. Different specimens subjected to fatigue cycles at stress levels of 60, 70, 80, and 90% of resistance to static compression were analyzed.

The specimens were introduced before and after subjecting them to fatigue in the CT scan AC. The fissures within the concrete and their development were compared. A 3DMA algorithm was used to calculate the "burn number" of the pores and fissures, a number that represents the distance of the voxels under analysis to the external surface of the pore. So, for example, the external voxels are assigned a value equal to zero. As the scan progresses into the interior of the pore or fissure, a higher value than the burn number is obtained [69]. Those voxels, in general within the value of 1, represented fissures of 1 voxel in width (**Figure 22**).

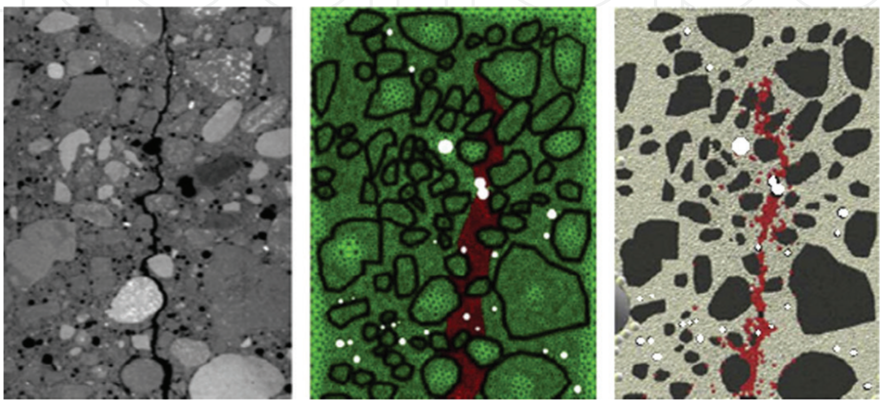

Figure 21. Results of three studies: real (left), using CT-Scan (middle), and FEM (right) [68].

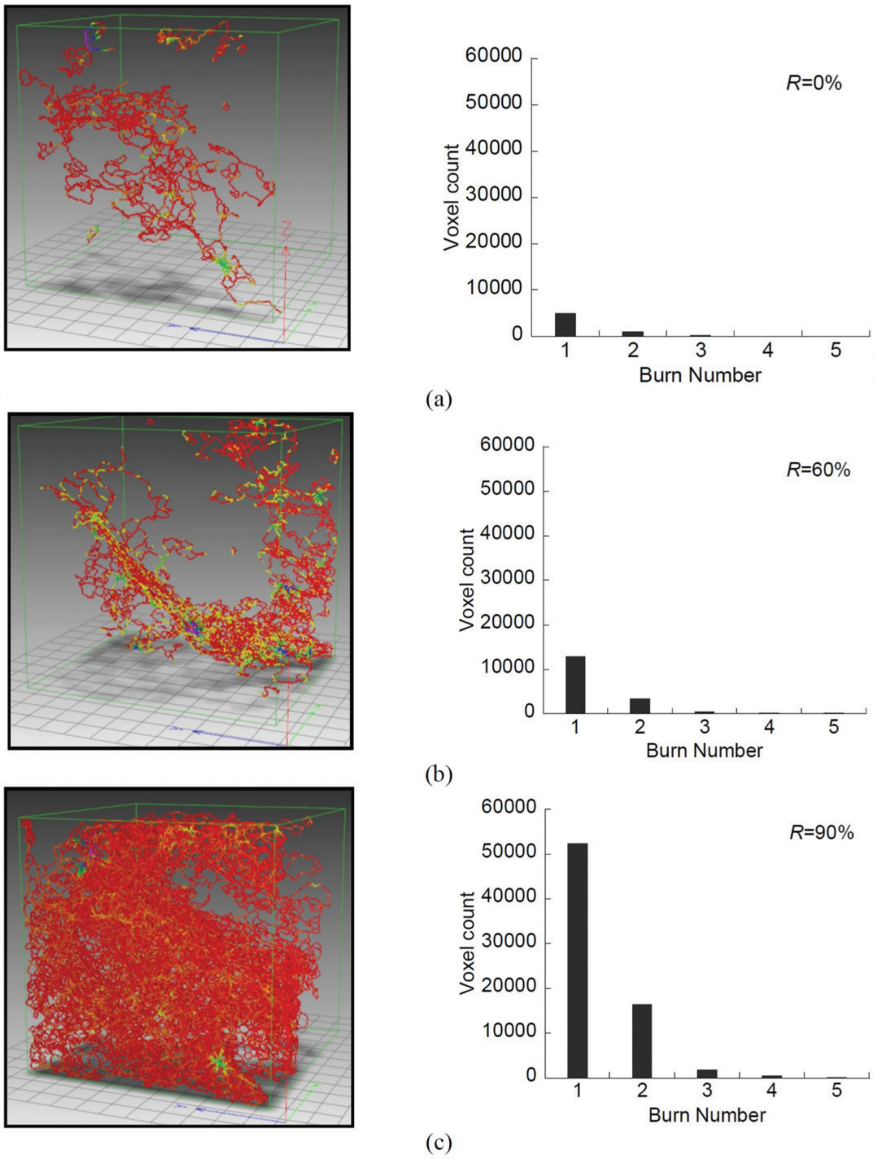

Figure 22. Spatial representation of damage (burn number) to different stress levels [69].

Following the tests, a growth in the internal damage was observed as the stress levels of the uniaxial cyclic loading increased.

9. Conclusions

CT scan technology is a powerful research tool, with wide use capabilities in many scientific fields, and not only in medicine.

In this chapter, a general review has been carried out by different fields of science and engineering in which CT scan technology is currently being used successfully. As can be seen, the possibilities of this technology are very large and allow relevant advances in the knowledge of the materials.

In the future, new equipment will be more powerful and more precise, which will allow us to see better the internal microstructure of our materials, which will help us to know them better and improve them, obtaining solutions adapted to each need.

Author details

Miguel A. Vicente*, Jesús Mínguez and Dorys C. González

*Address all correspondence to: mvicente@ubu.es

Department of Civil Engineering, University of Burgos, Spain

References

[1] Cnudde V, Boone MN. High-resolution X-ray computed tomography in geosciences: A review of the current technology and applications. Earth-Science Reviews. 2013;**123**:1-17

[2] Lautenschlager S. Reconstructing the past: Methods and techniques for the digital restoration of fossils. Royal Society Open Science. 2016;**3**:160342:1-18

[3] Tafforeau R, Boistel R, Boller E, Bravin A, Brunet M, Chaimanee Y, Cloetens P, Feist M, Hoszowska J, Jaeger JJ, Kay RF, Lazzari V, Marivaux L, Nel A, Nemoz C, Thibault X, Vignaud P, Zabler S. Applications of X-ray synchroton microtomography for non-destructive 3D studies of paleontological specimens. Applied Physics A. 2006;**83**(2):195-202

[4] Lautenschlager S. Cranial myology and bite force performance of Erlikosaurus andrewsi: A novel approach for digital muscle reconstructions. Journal of Anatomy. 2013;**222**(2):260-272

[5] Quam R, Lorenzo C, Martínez I, Gracia-Téllez A, Arsuaga JL. The bony labyrinth of the middle Pleistocene Sima de los Huesos hominins (Sierra de Atapuerca, Spain). Journal of Human Evolution. 2016;**90**(2):260-272

[6] López-Polín L, Ollé A, Cáceres I, Carbonell E, Bermúdez de Castro JM. Pleistocen human remains and conservation treatment: The case of a mandible from Atapuerca (Spain). Journal of Human Evolution. 2008;**90**:1-15

[7] Santos E, García N, Carretero JM, Arsuaga JL, Tsoukala E. Endocranial traits of the Sima de los Huesos (Atapuerca, Spain) and Petralona (Chalkidiki, Greece) Middle Pleistocene ursids. Phylogenetic and biochronological implications. Anales de Paléontologie. 2013;**100**(4):297-309

[8] Lorkiewicz-Muszynska D, Przystanska A, Kociemba W, Sroka A, Rewekant A, Zaba C, Paprzycki W. Body mass estimation in modern population using anthropometric measurements from computed tomography. Forensic Science International. 2013;**231**(1-3):405.e1-405.e6

[9] Ceperuelo D, Lozano M, Duran-Sindreu F, Mercadé M. Supernumerary fourth molar and dental pathologies in a Chalcolithic individual from the El Mirador Cave site (Sierra de Atapuerca, Burgos, Spain). HOMO-Journal of Comparative Human Biology. 2015;**66**(1):15-26

[10] Duval M, Martín-Francés L. Quantifying the impact of μCT-scanning of human fossil teeth on ESR age results. American Journal of Physical anthropology. 2017;**00**:1-8

[11] Immel A, Le Cabec A, Bonazzi M, Herbig A, Temming H, Schuenemann VJ, Bos KI, Langbein F, Harvati K, Bridault A, Pion G, Julien MN, Krotova O, Conard NJ, Münzel SC, Drucker DG, Viola B, Hublin JJ, Tafforeau P, Krause J. Effect of X-ray irradiation on ancient DNI in sub-fossil bones—guidelines for safe X-ray imaging. Scientific Reports. 2016;**6**:32969:1-14

[12] Zhang X, Blass J, Botha C, Reischig P, Bravin A Dik J. Process for the 3D virtual reconstruction of a microcultural heritage artifact obtained by synchrotron radiation CT technology using open source and free software. Journal of Cultural Heritage. 2012;**13**:221-225

[13] Lehmann EH, Vontobel, P, Deschler-Erb E, Soares, M. Non-invasive studies of objects from cultural heritage. Nuclear Instruments and Methods in Physics Research Section A. 2005;**542**:68-75

[14] Zhang K, Bao H. Research on the Application of Industrial CT for Relics Image Reconstruction. In: Asia-Pacific Conference on Information Processing. 2009. pp. 404-408

[15] Abel RL, Parfitt S, Ashton N, Lewis SG, Beccy-Scott C. Digital preservation and dissemination of ancient lithic technology with modern micro-CT. Computers & Graphics. 2011;**35**:878-884

[16] Morigi MP, Casali F, Bettuzzi M, Bianconi D, Brancaccio R, D'Errico V. Application of X-ray computed tomography to cultural heritage diagnostics. Applied Physics A. 2010;**100**:653-661

[17] Morigi MP, Casali F, Bettuzzi M, Bianconi D, Brancaccio R, Cornacchia S, Pasinia A, Rossi A, Aldrovandi A, Cauzzi D. CT Investigation of two paintings on wood tables by Gentile da Fabriano. Nuclear Instruments and Methods in Physics Research Section A. 2007;**580**:735-738

[18] Cesarini F, Martina MC, Ferraris A, Grilletto R, Boano R, Marochetti EF, Donadoni AM, Gandini G. Whole-body three-dimensional multidetector CT of 13 Egyptian human mummies. American Journal of Roentgenology. 2003;**180**:597-606

[19] Hu J, Qian Z, Wang D, Oeser M. Influence of aggregate particles on mastic and air-voids in asphalt concrete. Construction and Building Materials. 2015;**93**:1-9

[20] Liu P, Wang D, Oerser M, Alber S, Ressel W, Canon Falla G. Modelling and evaluation of aggregate morphology on asphalt compression behavior. Construction and Building Materials. 2017;**133**:196-208

[21] Yin A, Yang X, Zeng G, Gao H. Experimental and numerical investigation of fracture behavior of asphalt mixture under direct shear loading. Construction and Building Materials. 2015;**86**:21-32

[22] Chen XH, Wang DW. Fractal and spectral analysis of aggregate surface profile in polishing process. Wear. 2011;**271**(11-12):2746-2750

[23] Wang D, Wang H, Bu Y, Schulze C, Oeser M. Evaluation of aggregate resistance to wear with Micro-Deval test in combination with aggregate imaging techniques. Wear. 2015;**338-339**:288-296

[24] Zhang Y, Verwaal W, Van de Ven, MFC, Molenaar AAA, Wu SP. Using high-resolution industrial CT scan to detect the distribution of rejuvenation products in porous asphalt concrete. Construction and Building Materials. 2015;**100**:1-10

[25] Norambuena-Contreras J, Serpell R, Valdés Vidal G, González A, Schlangen E. Effects of fibres addition on the physical and mechanical properties of asphalt mixtures with crack-healing purposes by microwave radiation. Construction and Building Materials. 2016;**127**:369-382

[26] Jing Hu, Qian Z, Xue Y, Yang Y. Investigation on fracture performance of lightweight epoxy asphalt concrete based on microstructure characteristics. Journal of Materials in Civil Engineering. 2016;**28**(9):04016084:1-8

[27] Wang H, Zhang R, Chen Y, You Z, Fang J. Study on microstructure of rubberized recycled hot mix asphalt base X-ray CT technology. Construction and Building Materials. 2016;**121**:177-184

[28] Rinaldini E, Schuetz P, Partl MN, Tebaldi G, Poulikakos LD. Investigating the blending of reclaimed asphalt with virgin materials using rheology, electron microscopy and computer tomography. Composites: Part B. 2014;**67**:579-587

[29] Bultreys T, Boone MA, Boone MN, De Schryver T, Masschaele B, Hoorebeke LV, Cnudde V. Fast laboratory-based in micro-computed tomography for pore-scale research: Illustrative experiments and perspectives on the future. Advances in Water Resources. 2016;**95**:341-351

[30] De Kock T, Boone MA, De Schryver T, Van Stappen J, Derluyn H, Masschaele B, De Schutter G, Cnudde V. A pore-scale study of fracture dynamics in rock using X-ray micro-CT under ambient freeze-thaw cycling. Environmental Science & Technology. 2015;**49**:2867-2874

[31] Bultreys T, De Boever W, Cnudde V. Imaging and image-based fluid transport modelling at the pore scale in geological materials: A practical introduction to the current state-of-the-art. Earth-Science Reviews. 2016;**155**:93-128

[32] Lin Q, Al-Khulaifi Y, Blunt MJ, Bijeljic B. Quantification of sub-resolution porosity in carbone rocks by applying high-salinity contrast brine using X-ray microtomography differential imaging. Materials Characterization. 2014;**97**:150-160

[33] Bultreys T, Van Hoorebeke L, Cnudde V. Simulating secondary water flooding in heterogeneous rocks with variable wettability using an image-based, multiscale pore network model. Water Resources Research. 2016;**52**:6833-6850

[34] Charalampidou EM, Hall SA, Stanchits S, Viggiani G, Lewis H. Experimental characterization of shear and compaction band mechanisms in porous sandstone by a combination of AE and 3D-DIC. EDP Web of Conferences. 2010;**6**:22009:1-7

[35] Dewanckele J, De Kock T, Fronteau G, Derluyn H, Vontobel P, Dierick M, Van Hoorebeke L, Jacobs P, Cnudde V. Neutron radiography and X-ray computed tomography for quantifying wathering and water uptake processes inside porous limestone used as building material. Materials Characterization. 2014;**88**:86-99

[36] Boone MA, De Kock T, Bultreys T, De Schutter G, Vontobel P, Van Hoorebeke L, Cnudde V. 3D mapping of water in oolithic limestone at atmospheric and vacuum saturation using X-ray micro-CT differential imaging. Advances in Water Resources. 2016;**96**:306-366

[37] Yand S, Zhang R, Qu X. X-ray analysis of powed-binder separation during SiC injection process in L-shaped mould. Journal of European Ceramic Society. 2015;**35**:61-67

[38] Yand S, Zhang R, Qu X. Optimization and evaluation of metal injection molding by using X-ray tomography. Materials Characterization. 2015;**104**:107-115

[39] Wicke M, Luetje M, Bacaicoa I, Brueckner-Foit A. Characterization of casting pores in Fe-rich Al-Si-Cu alloys by microtomography and finite elements analysis. Procedia Structural Integrity. 2016;**2**:2643-2649

[40] Szkodo M, Bien A, Antoszkiewicz M. Effect of plasma sprayed and laser re-melted Al_2O_3 coatings on hardness and wear properties of stainless steel. Ceramics International. 2016;**42**:11275-11284

[41] Dahdah N, Limodin N, El Bartali A, Witz JF, Seghir R, Charkaluk E, Buffiere JY. Influence of the casting process in high temperature fatigue of A319 aluminium alloy investigated by in situ X-ray tomography and digital volume correlation. Procedia Structural Integrity. 2016;**2**:3057-3064

[42] Nemcko MJ, Wilkinson DS. On the damage and fracture of commercially pure magnesium using X-ray microtomography. Material Science & Engineering A. 2016;**676**:146-155

[43] Chan LC, Lu XZ, Yu KM. Multiscale approach with RSM for stress-strain behaviour prediction of micro-void-considered metal alloy. Materials & Design. 2015;**83**:129-137

[44] Hangai Y, Takahashi K, Yamaguchi R, Utsunomiya T, Kitahara S, Kuwazuru O, Yoshikawa N. Nondestructive observation of pore structure deformation behaviour of functionally graded aluminum foam by X-ray computed tomography. Materials Science & Engineering A. 2012;**556**:678-684

[45] Kuryntsev SV, Gilmutdinov AK. The effect of laser beam wobbling mode in welding process for structural steels. The International Journal of Advanced Manufacturing Technology. 2015;**81**(9):1683-1691

[46] Leitlmeier D, Degischer HP, Flankl HJ. Development of a foaming process for particulate reinforced aluminum melts. Advanced Engineering Materials. 2002;**4**(10):735-740

[47] Melenka GW, Lepp E, Cheung BKO, Carey JP. Micro-computed tomography analysis of tubular braided composites. Composite Structures. 2015;**131**:384-396

[48] Grammatikos SA, Kordatos EZ, Matikas TE, David C, Paipetis AS. Current injection phase thermography for low-velocity impact damage identification in composite laminates. Materials and Design. 2014;**55**:429-441

[49] Shen H, Nutt S, Hull D. Direct observation and measurement of fibre architecture in short fiber-polymer composite foam through micro-CT imaging. Composites Science and Technology. 2004;**64**:2113-2120

[50] Hayashi T, Kobayashi T, Takahashi J. Quantification of the void content of composite materials using soft X-ray transmittance. Journal of Thermoplastic Composite Materials. 2016;**00**:1-19

[51] Nikishkov Y, Airoldi L, Makeev A. Measurement of voids in composites by X-ray computed tomography. Composites Science and Technology. 2013;**89**:89-97

[52] McCombe GP, Rouse J, Trask RS, Withers PJ, Bond IP. X-ray damage characterisation in self-healing fibre reinforced polymers. Composites: Part A. 2012;**43**:613-620

[53] Wang Y, Burnett TL, Chai Y, Soutis C, Hogg PJ, Withers PJ. X-Ray computed tomography study of kink bands in unidirectional composites. Composite Structures. 2017;**160**:917-924

[54] Yu B, Bradley RS, Soutis C, Hogg PJ, Withers PJ. 2D and 3D imaging of fatigue failure mechanisms of 3D woven composites. Composites: Part A. 2015;**77**:37-49

[55] Grammatikos SA, Jones RG, Evernden M, Correia JR. Thermal cycling effects on the durability of a pultruded GFRC material for off-shore civil engineering structures. Composite Structures. 2016;**153**:297-310

[56] Jespersen KM, Zangenberg J, Lowe T, Withers PJ. Fatigue damage assessment of unidirectional non-crimp fabric reinforced polyester composite using X-ray computed tomography. Composites Science and Technology. 2016;**136**:94-103

[57] Stamopoulos AG, Tserpes KI, Prucha P, Vavrik D. Evaluation of porosity effects on the mechanical properties of carbon fiber-reinforced plastic unidirectional laminates by X-ray computed tomography and mechanical testing. Journal of Composite Materials. 2016;**50**(15):2087-2098

[58] Sencu RM, Yang Z, Wang YC, Withers PJ, Rau C, Parson A, Soutis C. Generation of micro-scale finite element models from synchrotron X-ray CT images for multidirectional carbon fibre reinforced composites. Composites: Part A. 2016;**91**:85-95

[59] Czabaj MW, Riccio ML, Whitacre WW. Numerical reconstruction of graphite/epoxy composite microstructure based on sub-micron resolution X-ray computed tomography. Composites Science and Technology. 2014;**105**:174-182

[60] Leite MB, Monteiro PJM. Microstructural analysis of recycled concrete using X-ray microtomography. Cement and Concrete Research. 2016;**81**:38-48

[61] du Plessis A, Olawuyi BJ, Boshoff WP, le Roux SG. Simple and fast porosity analysis of concrete using X-ray computed tomography. Materials and Structures. 2016;**49**(1):553-562

[62] Olawuyi BJ, Boshoff WP. Influence of SAP content and curing age on air void distribution of high performance concrete using 3D volume analysis. Construction and Building Materials. 2017;**135**:580-589

[63] Ponikiewski T, Katzer J, Bugdol M, Rudzki M. Steel fibre spacing in self-compacting concrete precast walls by X-ray computed tomography. Materials and Structures. 2015;**48**:3863-3874

[64] Herrmann H, Pastorelli E, Kallonen A, Suuronen JP. Methods for fibre orientation analysis of X-ray tomography images of steel fibre reinforced concrete (SFRC). Journal of Materials Science. 2016;**51**(8):3772-3783

[65] Vicente MA, Gonzalez DC, Mínguez J. Determination of dominant fibre orientations in fibre-reinforced high-strength concrete elements based on computed tomography scans. Nondestructive Testing and Evaluation. 2014;**29**:164-182

[66] Zirgulis G, Svec O, Geiker MR, Cwirzen A, Kanstad T. Influence of reinforcing bar layout on fibre orientation and distribution in slabs cast from fibre-reinforced self-compacting concrete (FRSCC). Journal of Materials Science. 2016;**17**(2):245-256

[67] Kim KY, Yun TS, Park KP. Evaluation of pore structures and cracking in cement paste exposed to elevated temperatures by X-ray computed tomography. Cement and Concrete Research. 2013;**50**:34-40

[68] Skarzynski L, Nitka M, Tejchman J. Modelling of concrete fracture at aggregate level suing FEM and DEM based on X-ray μCT images of internal structure. Engineering Fracture Mechanics. 2015;**147**:13-35

[69] Obara Y, Tanikura I, Jung J, Shintani R, Watanabe S. Evaluation of micro-damage of concrete specimens under cyclic uniaxial loading by X-ray CT method. Journal of Advanced Concrete Technology. 2016;**14**(8):433-443